

European renewable energy directive: Critical analysis of important default values and methods for calculating greenhouse gas (GHG) emissions of palm oil biodiesel

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Received: 28 May 2013 / Accepted: 26 March 2014 / Published online: 2 May 2014
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Abstract

Purpose The aim of this paper is to evaluate assumptions and data used in calculations related to palm oil produced for biodiesel production relative to the European Renewable Energy Directive (EU-RED). The intent of this paper is not to review all assumptions and data, but rather to evaluate whether the methodology is applied in a consistent way and whether current default values address relevant management practices of palm oil production systems.

Methods The GHG calculation method provided in Annex V of the EU-RED was used to calculate the GHG-emissions from palm oil production systems. Moreover, the internal nitrogen recycling on the plantation was calculated based on monitoring data in North Sumatra.

Results and discussion A calculation methodology is detailed in Annex V of the EU-RED. Some important aspects necessary to calculate the GHG emission savings correctly are insufficiently considered, e.g.:

- “Nitrogen recycling” within the plantation due to fronds remaining on the plantation is ignored. The associated organic N-input to the plantation and the resulting nitrous oxide emissions is not considered within the calculations, despite crop residues being taken into account for annual crops in the BIOGRACE tool.

- The calculation of GHG-emissions from residue and waste water treatment is inappropriately implemented despite

being a hot-spot for GHG emissions within the life cycle of palm oil and palm oil biodiesel. Additionally, no distinction is made between palm oil and palm kernel oil even though palm kernel oil is rarely used for biodiesel production.

- The allocation procedure does not address the most relevant oil mill management practices. Palm oil mills produce crude palm oil (CPO) in addition either nuts or palm kernels and nut shells. In the first case, the nuts would be treated as co-products and upstream emissions would be allocated based on the energy content; in the second case the kernels would be treated as co-products while the shells are considered as waste without upstream emissions. This has a significant impact on the result or GHG savings, respectively.

- It is not specified whether indirect GHG emissions from nitrogen oxide emission from the heat and power unit of palm oil mills should be taken into account.

Conclusions and recommendations In conclusion, the existing calculation methodology described in Annex V of the EU-RED and default values are insufficient for calculating the real GHG emission savings from palm oil and palm oil biodiesel. The current default values do not reflect relevant management practices. Additionally, they protect poor management practices, such as the disposal of empty fruit bunches (EFB), and lead to an overestimation of GHG savings from palm oil biodiesel. A default value for EFB disposal must be introduced because resulting GHG emissions are substantial. Organic nitrogen from fronds must be taken into account when calculating real GHG savings from palm oil biodiesel. Further, more conservative data for FFB yield and fugitive emissions from wastewater treatment should be introduced in order to foster environmental friendly management options. Moreover, credits for bioenergy production from crop residues should be allowed in order to foster the mobilization of currently unused biomass.

Responsible editor: Hans-Jürgen Garvens

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Keywords Allocation factor · FFB yield · Fugitive methane emission · Organic nitrogen

1 Introduction

In June 2009, the European Parliament adopted the Directive 2009/28/EC as part of the new Renewable Energy Directive (EU-RED). It is supposed to amend and subsequently repeal the Directive 2003/30/EC on the promotion of biofuels (Buratti and Fantozzi 2010; EC 2003). The EU-RED sets a mandatory overall target of a 20 % share of energy from renewable sources of the EU's gross final consumption in 2020 (EU 2009). Additionally, the EU-RED and the Fuel Quality Directive establish sustainability criteria for biofuels; the only quantitative criterion is that greenhouse gas (GHG) emission savings must be at least 35 % compared to fossil fuels. This percentage increases to at least 50 % in 2017 and to 60 % in 2018 for biofuels produced in new installations. The EU-RED does not set targets for specific sectors, except for transport. The share of energy from renewable sources in all forms of transport must be at least 10 % of the final consumption of energy in transport by 2020. In 2012, an amendment to Directive 98/70/EC2 ("the Fuel Quality Directive") introduced a mandatory target to achieve a 6 % reduction in the greenhouse gas intensity of fuels used in road transport by 2020.

Diesel represents the most important transport fuel in Europe. In some member states up to 80 % of transport fuel is diesel, due to the difference in tax for diesel and gasoline. Originally, the EU aimed at preserving its energy independence by increasing the use of diesel engines, more economical in fuel consumption. In 2011, first-generation biodiesel production in Europe was under pressure from reduced national and European incentives and more competitive market prices for vegetable oils for food, making it more profitable for farmers to sell oilseeds to the food industry rather than to the biodiesel industry. This economic factor had a major impact on biodiesel production in Europe. Biodiesel production decreased from 9.6 million tons in 2010 to 8.8 million tons in 2011, while the consumption of biodiesel increased 12 million tons to 13.6 million tons in 2011.

Rapeseed biodiesel is a very popular indigenous European biofuel (Thamsiriroj and Murphy 2010b). However, it is difficult for rapeseed biodiesel to meet the 50 % GHG reduction target without significant improvement in N fertiliser management and conversion technology.

Tropical biofuels such as palm oil biodiesel tend to be more climate-friendly, due to the use of residues and byproducts to satisfy parasitic energy demands as long as no land use change is involved (de Vries et al. 2010; Thamsiriroj and Murphy 2010a).

The Joint Research Centre Ispra (JRC) (Edwards 2007) has provided default values for GHG emission savings of 22 biofuel production pathways (Annex V of the Renewable Energy Directive or Annex IV of the Fuel Quality Directive). The project BioGrace is setup to harmonise calculations of biofuel GHG emissions based on that default values and thus support the implementation of the EU Renewable Energy Directive (2009/28/EC) and the EU Fuel Quality Directive (2009/30/EC) into national laws. The GHG savings from biodiesel produced from palm oil are 56 % when current default values are applied.

The aim of this paper is to analyse the information and methods used by JRC regarding GHG calculations for palm oil and to evaluate assumptions and data for palm oil biodiesel production.

2 GHG calculation methodology

The EU-RED defines a formula that enables economic operators to calculate emission reductions. This formula incorporates all life cycle stages. Under the EU-RED, use of this formula when calculating GHG-savings from biofuels is mandatory. Moreover the EU-RED dictates that emissions from the manufacture of machinery and equipment shall not be taken into account. The relative reduction of GHG emissions compared to fossil fuels is defined as: Emission reduction = $(E_f - E)/E_f$

Where:

$$E_f = \text{total emissions from fossil fuel (for diesel } 83.6\text{gCO}_{2\text{eq}}/\text{MJ})$$

$$E = \text{total emissions from biofuels}$$

The BIOGRACE-project is setup to harmonise calculations of biofuel greenhouse gas (GHG) emissions based on that default values. BioGrace provides an EXCEL-based calculation tool¹ for different biofuel pathways based on the methodological guidelines outlined in Annex V. A number of national calculation tool for biofuels as well as commercial carbon footprint

¹ www.bigrace.net (accessed 06.03.2012, version 4b)

tools such as UMBERTO® CARBON FOOTPRINT are based on the BIOGRACE calculator and thus the default values provided by JRC (Edwards 2007).² However, some important aspects necessary to calculate the GHG savings from the use of palm oil directly or as feedstock for biodiesel correctly are just insufficiently considered.

2.1 Land use change

Direct and indirect land use change are recognized as an important issue regarding GHG savings but also food security (Aalders and Aitkenhead 2006; Banse et al. 2011; Bringezu 2009; Bringezu et al. 2012; Hedal Kløverpris et al. 2010; Saikku et al. 2012; Secchi et al. 2011); therefore, the European commission has proposed amendments to the Directive 2009/28/EC on the 17 October 2012. It is proposed to include indirect land use emission factors for conventional biofuels in order to encourage a greater market penetration of advanced (low ILUC) biofuels (EC 2012). In the EC proposal, the following is stated:

Indirect land-use change emissions estimates are calculated through modelling, which, notwithstanding recent improvements made in the science, remain sensitive to and may vary according to the modeling framework and assumptions made.

ILUC-factors are often controversial (O'Hare et al. 2011; Kim and Dale 2011; Di Lucia et al. 2012; Gawel and Ludwig 2011) and might be relevant in the future but they are not part of the current legislation and therefore not considered here.

2.2 Indirect GHG emissions

The EU-RED does not explicitly state if the range of indirect indirect GHG emissions have to be taken into account. IPCC provides emission factors for calculating indirect nitrous oxide emissions from ammonia, nitrogen oxide and nitrate. Within the BIOGRACE calculation tool, only just indirect emissions from ammonia and nitrate is considered. This is inconsistent

from a methodological point of view, although that might not alter results significantly.

3 Analysis and results

3.1 System boundary and FFB yield

Plantation managers report generally the productive area of the plantation and the associated fresh fruit bunches (FFB) yield. The yield per hectare is overestimated by approximately 10 % when the productive area instead of the plantation area is reported and an average life span for oil palms of 25–30 years is assumed. The whole life cycle of oil palms includes the nursery stage (3 month in pre-nursery and 9 month in main nursery) and the early growing stage of immature palms (2–3 years), in addition to the productive harvest period (Kaewmai et al. 2012). In general, harvest starts in 3 or 4 years. Table 1 shows the FFB yield data from 30 plantations in North Sumatra, a favorite region for oil palm plantations in Indonesia, during the time period from 1986 to 2008.

The average annual yield of that plantation was 20.6 t FFB ha⁻¹ productive area and 18.9 t FFB ha⁻¹ plantation area. Table 2 summaries reported FFB yield in different countries.

The yield of FFB depends on a number of factors and ranges from 2 t FFB ha⁻¹ to more than 30 t FFB ha⁻¹. In Cameroon, the dramatic differences in yield between smallholders and industrial plantations accrue from poor fertilization according to Rafflegeau et al. (2010). Malins refers to FAO-statistics and mentioned average FFB yield in Malaysia of 21 t ha⁻¹ and in Indonesia of 17 t ha⁻¹ (Malins 2012). JRC assumed an annual FFB yield of 19 t ha⁻¹ as a default value. This is a reasonable assumption for ordinary managed industrial plantations in Malaysia and potentially also Indonesia, which are the main palm oil producers. However, this value is far too high for poorly managed plantations and other regions of the world, where climate and soil conditions for oil palms are not as favorable (Chavalparit 2003; Chavalparit et al. 2006; Arrieta et al. 2007; Pleanjai and Gheewala 2009; Siriwardhana et al. 2009).

An average yield of 14.2 t FFB ha⁻¹ productive area and 12.8 t FFB ha⁻¹ plantation area results when yields reported in Table 2 from Malaysia and Indonesia, as well as yields from small-holders are ignored.

3.2 Carbon sequestration

Perennial crops such as oil palms accumulate carbon during their life time (25–30 years). Henson (1999) showed that mature oil palm on coastal soil in Malaysia caused a net carbon fixation of 11.0 t ha⁻¹ year⁻¹ based on the eddy covariance technique. However, a large proportion of the

² Other GHG calculators for palm oil such as the GHG calculator of the Roundtable of Sustainable Palm Oil (RSPO) or the GREET-tool are beyond the scope of this paper, because those tools do not apply the calculation methodology outlined in Annex V of the EU-RED.

Table 1 FFB yield from age 3 to 25 years in North Sumatera^a

Palm age (years)	Number of samples ^a	Yield (t/ha)		
		Minimum	Maximum	Average
3	83	1.75	9.03	4.08
4	116	4.73	23.14	12.12
5	118	6.96	29.60	16.41
6	111	8.30	31.43	18.40
7	78	13.21	28.01	20.98
8	70	16.18	33.26	22.04
9	59	18.25	29.72	23.90
10	65	18.10	31.06	24.18
11	57	18.40	32.36	24.51
12	54	16.90	32.28	24.50
13	54	18.73	33.00	24.68
14	66	16.20	34.13	23.13
15	64	14.42	32.49	22.82
16	58	15.71	36.58	22.70
17	46	15.14	36.11	22.52
18	36	16.20	34.35	21.71
19	21	18.22	29.80	22.54
20	20	17.49	30.18	21.82
21	16	18.13	30.30	21.04
22	13	17.48	26.08	20.71
23	12	14.06	25.04	20.04
24	10	16.22	21.97	19.67
25	8	15.81	24.67	19.16
Average (3 to 25 years)				20.59
Average (0 to 25 years)				18.95

^a Data were collected from 30 estates in North Sumatera in the period of 1986 to 2008

^b Each state managed more than one palm age group

assimilated carbon is exported to the oil mill (Melling et al. 2010). The temporary storage of carbon in trunks might improve the GHG balance of palm plantations (Lam et al. 2009), but there is no generally accepted method to quantify temporary carbon storage (Levasseur et al. 2012). The role of soil organic matter in LCA is the subject of ongoing discussions (Müller-Wenk and Brandão 2010; Brandão et al. 2011). Whether or not palm oil plantations are a net sink or source of carbon depends on the soils, climate, and cultivation and residue management practices, but also on the history of the site (Melling et al. 2005; 2006; 2010).

3.3 Organic nitrogen

In order to harvest FFB, the fronds beneath the fruit bunch have to be pruned and left on the ground. Fronds decompose

Table 2 Annual FFB yield per hectare in different countries

	Yield t FFB/ (ha*a)	Country
Reference		
(Schmidt 2004)	18.3	Malaysia
GABI ^a	19.6	Malaysia
(Wicke et al. 2007; 2008)	25	Malaysia
(Jungbluth et al. 2007)	25	Malaysia
(Chen 2008)	19	Malaysia
(Dumelin et al. 2002)	30	Malaysia
(Tarmizi et al. 2006)	30	Malaysia
(Cocklin 1989)	20	Malaysia
(Wahid et al. 2005)	20	Malaysia
(Ng and Thamboo 1967)	20	Malaysia
cited in (Corley and Tinker 2003)		
(Goh 2005)	20	Malaysia
(Sulaiman et al. 2011)	19.6	Malaysia
(Kamahara et al. 2010)	17.6	Indonesia
(Malins 2012)	17.2	Indonesia
(Papong et al. 2010)	16.5	Thailand
(Kittikun et al. 2000)	12.3	Thailand
(Pleanjai et al. 2004)	17.2	Thailand
(Kaewmai et al. 2012)	16.9	Thailand
(Henson et al. 2011)	16.5	Columbia
(Edward et al. 1999)	8–10	Nigeria
(Agvei-Dwarko 2010)	12	Ghana
(S. Adjei-Nsiah 2012)	3–6	Ghana (smallholders)
	11–14	(industrial plantations)
(Achten et al. 2010)	13	Cameroon
(Rafflegau et al. 2010)	2–14	Cameroon
	14–16	(smallholders)
		(industrial plantations)

^a PE-International GABI documentation palm oil dataset

and nitrous oxide is formed as a by-product of nitrification and denitrification processes in the soil.

Samples of pruned fronds were collected from Aek Pancur Research Station, Deli Serdang, North Sumatra. Due to the limited palm ages in the research station, sampling was only conducted on 11 groups of palm between 4 to 25 years of age. For each group of palm age, one pruned frond from three normal palms was collected, so there were three pruned fronds from three normal palms in each palm age group. Each frond was divided into three parts: rachis, leaflets, and midribs. Dry matter, moisture content, and nitrogen contents were determined after drying the samples at 85 °C for 48 h. Total pruned fronds dry matter and total N content per hectare were then calculated by considering the average number of pruned fronds per palm and palm population per hectare (132 palms per hectare, 24 pruned fronds per

Table 3 Dry matter of pruned fronds

Palm age [a]	Rachis [g]	Midrib [g]	Leaflet [g]	total/frond [g]	t/ha
4	755	54	265	1,074	3.4
6	1,274	163	500	1,936	6.1
8	1,979	177	666	2,823	8.9
10	2,098	181	841	3,121	9.9
12	2,190	190	975	3,355	10.6
14	2,331	191	1,028	3,550	11.2
16	2,529	200	1,072	3,801	12.0
18	2,580	203	1,111	3,894	12.3
21	2,571	212	1,142	3,926	12.4
23	2,611	224	1,152	3,987	12.6
25	2,702	236	1,161	4,099	13

palm per year). The dry matter of pruned fronds is shown in Table 3 and the nitrogen content of rachis, leaflets, and midribs in Table 3 for oil palms of different age:

According to the measured data presented in Tables 3 and 4, the average organic nitrogen content of fronds is 76 kg N ha⁻¹ year⁻¹ over the whole life cycle of the plantation when just the productive area is taken into account.

According to literature data, the dry matter of fronds vary between 8.6 and 13.8 t ha⁻¹ year⁻¹ (Ng et al. 1968; Corley et al. 1971), and their nitrogen content between 0.75 and 1.3 % (Khalid et al. 2000; Wan Zahari et al. 2003; Idris 2003). Hence, the annual organic nitrogen recycling on oil palm plantation can range between 64.5 to 180 kg ha⁻¹, with an average value of approximately 100 kg nitrogen ha⁻¹. IPCC treats residue from perennial crops differently from annual crops for the latter the area is renewed annually while for perennial crops the area is renewed every X years, which can be expressed as factor 1/X (IPCC

Table 4 Nitrogen content of rachis, midrib and leaflet

Palm age [a]	Rachis [%N]	Midrib [%N]	Leaflet [%N]	kg N/ha
4	0.38	0.65	1.88	26.0
6	0.42	0.69	1.9	50.6
8	0.32	0.46	1.69	58.3
10	0.39	0.48	1.58	70.8
12	0.39	0.47	1.61	79.6
14	0.32	0.55	1.57	78.1
16	0.36	0.58	1.7	90.2
18	0.38	0.48	1.65	92.2
21	0.31	0.52	1.72	91.0
23	0.34	0.46	1.64	91.2
25	0.38	0.54	1.51	92.1

2006a).³ Organic nitrogen from harvest residues of palms is currently ignored in GHG calculations in the BIOGRACE-tool. This results in overestimates of GHG savings from palm oil and palm oil biodiesel, respectively. Choo does not consider associated GHG emissions from pruned fronds (Choo et al. 2011) and Wicke et al. (2008) argues that empty fruit bunches (EFB) and fronds are piled in thin layers on the ground and therefore do not cause GHG emissions. That might be valid for the formation of methane but does not hold for nitrous oxide formation. The annual precipitation in Malaysia and Indonesia is 2,000–4,000 mm year⁻¹. During the degradation of the fronds, a significant amount of organic nitrogen is leached to the soil. The organic matrix is further decomposed, and nitrous oxide is formed as a by-product of nitrification and denitrification processes. Consequently, residues from oil palms should not be treated significantly different from residues of other crops. Figure 1 shows mass flows of a typical palm oil mill.

The only organic nitrogen considered in the BIOGRACE-tool is from compost derived from EFB, which is assumed to be 586 kg EFB compost_{DM} ha⁻¹ year⁻¹ containing 6 kg N. According to Fig. 1, approximately 0.23 t EFB occurs when 1 t FFB is processed. The default yields of 19 t FFB ha⁻¹ results in 4.3 t EFB ha⁻¹. When co-composting of EFB and palm oil mill effluent (POME) is assumed, the amount of compost is approximately 400 kg compost t⁻¹ EFB or 92 kg compost t⁻¹ FFB (Stichnothe and Schuchardt 2010). The average dry matter content of EFB compost is 50 %, and the nitrogen content is 26.3 kg N t_{dm}⁻¹, and that result in 23 kg N ha⁻¹ due to the EFB compost application and differs to the BIOGRACE calculation by 17 kg organic N ha⁻¹. Thus, the current value for organic nitrogen from EFB compost is underestimated. Waste management options such as co-composting, returning EFB to the plantation, and using POME for irrigation purposes are not considered by JRC, but should be according to Annex V (11). GHG emissions from the composting process are not considered in the current version of the BIOGRACE tool, which is contrary to Annex V(11). GHG emissions resulting from the composting process are approximately 15.6 kg CO_{2eq} t⁻¹ FFB or 296 kg CO_{2eq} ha⁻¹ assuming that the amount of EFB derived from 1 ha is returned as compost to 1 ha (Stichnothe and Schuchardt 2010).

The amount of POME is 0.65 m³ t⁻¹ FFB and the dry matter content is 41 kg t⁻¹. The nitrogen content of POME is 18.3 kg N t_{dm}⁻¹. If treated POME is used for irrigation, additional 9 kg organic nitrogen is applied; this option is not foreseen in the BIOGRACE-tool (version 4b).

3.4 Methane emissions

Emissions from POME treatment are assumed to be zero by JRC, which is not a realistic assumption. Even fugitive

³ IPCC Vol. 4 Equation 11.6, see $Frac_{renew(t)}$

methane emissions of modern biogas plants ranges from 1.5 to 3.0 % (FNR 2009; Flesch et al. 2011); if the effluent of the biogas plant is stored in open storage facilities fugitive methane emissions can approach 9 % (FNR 2009). UNFCC guidance suggests that for small CDM projects, methane emissions due to physical leakages from the digester and recovery system should be estimated using a default factor of 0.05 m³ biogas leaked/m³ biogas (UNFCC 2010). Concerning anaerobic digestion of organic waste the IPCC stated:

Emissions of CH₄ from such facilities due to unintentional leakages during process disturbances or other unexpected events will generally be between 0 and 10 percent of the amount of CH₄ generated. In the absence of further information, use 5 percent as a default value for the CH₄ emissions (IPCC 2006b).

Using the mass flow ratio from Fig. 1, a typical POME composition and measured data from fixed bed anaerobic digester and lagoons (Wulfert et al. 2002), then 5.7 m³ CH₄t⁻¹ FFB can be produced, which results in 0.28 m³ or 0.2 kg fugitive methane emissions.⁴ Those emissions occur when biogas is flared but also when it is used. However, if the biogas is used for electricity production or transport fuel GHG emission, credits will be provided. The utilization of POME for biogas production and the subsequent use of biogas would reduce GHG emissions. The same applies when surplus biomass, e.g., nut shells are used for bioenergy production. However, in Annex V (16) states:

...In accounting for that excess electricity, the size of the cogeneration unit shall be assumed to be the minimum necessary for the cogeneration unit to supply the heat that is needed to produce the fuel. The greenhouse gas emission saving associated with that excess electricity shall be taken to be equal to the amount of greenhouse gas that would be emitted when an equal amount of electricity was generated in a power plant using the same fuel as the cogeneration unit.

The EU-RED takes a conservative approach, which does not provide sufficient incentives for producing electricity from residues at plantations. However, this production provides a significant GHG savings compared to the average electricity mix in palm oil producing countries. A more progressive option would be to assume the emissions savings associated with an equal amount of electricity were generated in a power plant using the average fuel mix of a country.

The management of biogas plants and covered ponds is paramount to GHG emission calculations (Kaewmai et al. 2013) and should be taken into account. Moreover, if EFBs are dumped, the current minimum requirement of 35 % of GHG savings cannot be achieved (Stichnothe and Schuchardt 2011). Consequently, this option should be added to the default values for palm oil similar to that “without methane capture.”

3.5 Palm oil and palm kernel oil

The typical oil extraction rate (OER) of CPO from FFB in palm oil mills ranges in different countries from 16–26 % (Yee et al. 2009; Schmidt 2004; Chavalparit 2003; Thamsirirotj and Murphy 2009; Carter et al. 2007), JRC assumed 22.2 %.

JRC does not distinguish between CPO and kernel palm oil (PKO). PKO is mainly produced in specialized mills and it is rarely used for biodiesel production (Rettenmaier et al. 2007; Kaewmai et al. 2012; Manik and Halog 2013). The price of PKO is 20–50 % higher than the price of CPO.⁵ Hence, it does not make economic sense to use PKO for biodiesel. The distinction of CPO and PKO influences the allocation factor for CPO.

The kernels from several palm oil mills are usually collected and transported to a separated kernel oil mill. The nutshells are partly used both for on-site energy production and sold as an energy carrier. Nut shells are considered as residue in the EU-RED.

Option 1: Kernels are transported to separate palm kernel mills. The low calorific value (LCV) of kernels is between 24 and 28 MJ kg⁻¹, while the LCV of CPO is 36 MJ kg⁻¹. Using these calorific values and the mass flows according to Fig. 1, then the allocation factor (AF) for CPO (AF_{CPO}) should be:

$$AF_{CPO} = \frac{mass_{CPO} * LCV_{CPO}}{(mass_{CPO} * LCV_{CPO} + mass_{kernels} * LCV_{kernels})} = 0.79$$

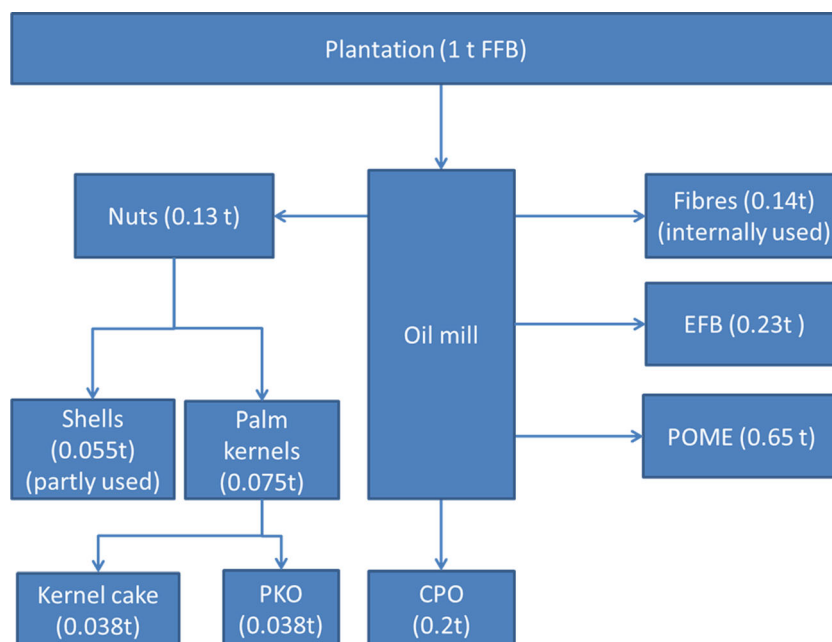
Oil mills with optimized boilers can also export the whole nuts rather than the kernels. In that case, difficulty occurs when nuts instead of the kernels are sold. Then, the calorific value of the nut shells are part of the coproduct, and GHG emissions should be allocated according to energy content as requested by the EU-RED.

Option 2: Nuts are transported to the PKO mill then the shells are part of the coproduct and must be taken into account. The LCV of nut shells is 18 MJ kg⁻¹. The allocation factor for CPO is then:

$$AF_{CPO} = \frac{mass_{CPO} * LCV_{CPO}}{(mass_{CPO} * LCV_{CPO} + mass_{kernels} * LCV_{kernels} + mass_{shells} * LCV_{shells})} = 0.71$$

⁴ Methane density ~0.72 kg m³

⁵ Webseite http://econ.mpob.gov.my/upk/monthly/bh_monthly_12.htm

Fig. 1 Typical mass flow values of CPO production

Not considering nuts or kernels as coproducts would be contrary to the text of paragraph (81) of the EU-RED:

Co-products from the production and use of fuels should be taken into account in the calculation of greenhouse gas emissions

JRC default values and values from relevant literature are shown in Table 5. The emphasized figures are used to calculate the GHG savings shown in Table 6.

The GHG savings from palm oil biodiesel depend on a number of management options, e.g., disposal of EFB, efficient biogas capture, composting practice, and so on. Therefore, we have chosen three relevant management options:

1. EFB is disposed and biogas is captured,
2. EFB is returned to the plantation and biogas is captured,

3. EFB and POME is co-composted and returned to the plantation.

We have assumed that only CPO is utilised for biodiesel production and used the figures emphasized in Table 5 for calculating the GHG emissions per life cycle stage as well as the total GHG savings. Table 6 presents the results of this calculation, and compares them to the results provided by the BIOGRAVE tool.

We have used a conservative data for the calculation and none of the chosen option would meet the GHG reduction target of 50 %. However, the results in Table 6 also indicate that palm oil biodiesel can provide substantial GHG savings if good management practices are used.

Table 5 Comparison of some default values (Edwards 2007) and values derived or calculated from literature

	JRC/Biograce	Literature values	Comment
Allocation factor (at oil mill)	0.95	0.71–0.79	
FFB yield (t FFB/ha*a))	19	2–30 (average 14)	
EFB compost [kg N ha ⁻¹]	6	Approximately 23	
Fronds [kg N ha ⁻¹]	0	75–100	If equally treated as annual crops
Irrigation with POME [kg N ha ⁻¹]	0	9	If applicable
Direct N ₂ O emissions due to organic N [kg N ₂ O N ha ⁻¹]	0.06	0.27–0.36	Assuming 75–100 kg organic N
Field emissions due to organic N [kg CO _{2eq} ha ⁻¹]	17.9	126–167	
Down-stream emissions from co-composting [kg CO _{2eq} ha ⁻¹]	0	296/600/2909	Good/average/bad composting practice
Fugitive methane emissions [kg CO _{2eq} t FFB]	0	6.2–13.4	Assuming 5 % or 10 % fugitive emissions

Table 6 Comparison of results calculated by BIOGRACE using default values and results according to suggestions from Table 5

Life cycle stage	Biograce value (with CH ₄ capture)	1. EFB disposal and CH ₄ -capture	2. With EFB use and CH ₄ -capture	3. Co-composting of EFB and POME
Cultivation, including organic N [g CO _{2eq} MJ ⁻¹]	15.59	16.91	24.81	24.81
Oil extraction at mill [g CO _{2eq} MJ ⁻¹]	0	0	0	0
EFB disposal [g CO _{2eq} MJ ⁻¹]	Not considered	24.15	–	–
Composting [g CO _{2eq} MJ ⁻¹]	0	–	–	0.13
Fugitive emissions [g CO _{2eq} MJ ⁻¹]	0	1.62	1.62	–
Refining of oil [g CO _{2eq} MJ ⁻¹]	1.06	1.06	1.06	1.06
Esterification [g CO _{2eq} MJ ⁻¹]	17.51	17.51	17.51	17.51
Transport [g CO _{2eq} MJ ⁻¹]	5.18	5.18	5.18	5.18
Filling station [g CO _{2eq} MJ ⁻¹]	0.44	0.44	0.44	0.44
Sum (unallocated) [g CO _{2eq} MJ ⁻¹]	39.3	66.42	49.83	48.69
Sum allocated [g CO _{2eq} MJ ⁻¹]	36.9	55.46	43.01	41.87
GHG savings [%]	56	33.7	48.9	49.91

4 Summary

The average yield of FFB depends on a number of factors and ranges in Malaysia from less than 15 t FFB ha⁻¹ to more than 25 t FFB ha⁻¹ (Tarmizi et al. 2006). The relation between the palm oil plantations and palm oil mills can be rather complex. Palm oil mills can be supplied by one particular plantation or by various plantations with sometimes different management systems. In general, FFB yield varies between countries or even regions within one country, but also the performance of plantations and oil mills can differ significantly. Obviously, it is difficult to provide “accurate” data. However, default values should not ignore relevant emissions and should not protect poor management practice on palm oil plantations and mills such as the disposal of EFB.

Benoist has identified two main challenges for calculating GHG-emissions of agricultural systems:

Getting a better understanding and knowledge about biochemical reactions involved in N₂O emissions, and having available local data about soils (Benoist et al. 2012).

In general, the role of organic nitrogen, e.g., from fronds remaining or added to the plantation is not properly addressed in Annex V. The associated organic nitrogen input to the plantation and the resulting nitrous oxide emissions are not considered in the calculations, despite crop residues are taken into account for annual crops in the BIOGRACE tool. The nitrous oxide emissions would increase from 3.51 to 4.89 kg ha⁻¹ year⁻¹, if the organic nitrogen from fronds (100 kg N ha⁻¹ year⁻¹) is taken into account.

The calculation of GHG emissions from residue and waste water treatment is inappropriately implemented despite being a hot-spot for GHG emissions within the life cycle of palm oil and biodiesel from palm oil (Stichnothe and Schuchardt 2010; 2011; Vijaya et al. 2008; Choo et al. 2011; Yoshizaki et al. 2013; Poh and Chong 2009). Default values provided by JRC ignore GHG emissions from EFB disposal, although these emissions are considerable. Covered ponds or biogas plants are considered to cause no fugitive methane emissions according to (Edwards 2007) while related methodologies, e.g., for CDM-projects assume 5–10 % methane loss. The latter assumption is supported by FNR (2009), where fugitive methane emissions from 61 biogas plants in Germany have been measured.

CPO and PKO are different products but not treated as such in AnnexV, although PKO is produced in specialized mills and is rarely used for biodiesel production. Consequently, including an allocation factor of 0.96 due to kernel cake in the calculation as done in the BIOGRACE-tool is wrong, because kernel cake is a coproduct from PKO-production but not from CPO-production. Palm oil mills produce crude palm oil (CPO) and in addition either nuts or palm oil kernels and nut shells (Wicke et al. 2008; Rettenmaier et al. 2007; Kaewmai et al. 2012). In the first case, the nuts would be treated as coproducts, and upstream emissions would be allocated based on the energy content; in the second case, the kernels would be treated as coproducts while the shells are considered as waste without upstream emissions. The allocation factors for these two options are 0.71 and 0.79, respectively. Those allocation factors are more appropriate for oil mills than the current allocation factor of 0.96. Allocation factors should reflect the most relevant management practices, because they can influence the calculated GHG savings considerably.

5 Conclusions

The current default values do not represent common management practices on palm oil plantation and palm oil mills. In conclusion, the existing calculation methodology described in Annex V is not consistent, and the provided default values for palm oil are overestimating GHG savings from palm oil and palm oil biodiesel.

Important aspects necessary to calculate the GHG savings from the use of palm oil directly or as feedstock for biodiesel are just insufficiently considered in (Edwards 2007) and consequently also in the BIOGRACE-tool.

The major shortcomings regarding methodological issues and data are:

- System boundary (the nursery stage and early growing stage is not considered)
- The assumed FFB yield is too high
- No distinction is made between CPO and PKO even though PKO is rarely used for biodiesel production
- The allocation factor is flawed and should be 0.71 or 0.79 depending on the management practice of oil mills
- Organic nitrogen from fronds and resulting nitrous oxide emissions (N_2O) are ignored
- Waste management practice, e.g., EFB if dumped and fugitive methane emissions from POME treatment
- The use of residues from oil palm plantations and palm oil mills for electricity production is not encouraged despite having a huge potential for GHG savings

In order to overcome these shortcomings, there is an urgent need to update default values and calculation procedure for palm oil. Default values should reflect a relevant management practices at palm oil plantations and mills and should not protect poor management practices such as disposal of EFB. Organic nitrogen from fronds has to be taken into account for calculating real GHG savings from palm oil biodiesel. More conservative data for FFB yield and fugitive emissions from wastewater treatment should be introduced; some relevant data are shown in Table 5. Additionally, credits for bioenergy production from crop residues should be allowed in order to foster the mobilization of currently unused biomass. When combating climate change is the aim, then it does not matter where the GHG reduction occurs.

Acknowledgments This research was supported by funding from the International Bureau of the Federal Ministry of Education and Research in Germany (Project ID: 7017). We would like to thank the anonymous reviewers for their constructive criticism that has helped to improve the manuscript.

References

- Aalders IH, Aitkenhead MJ (2006) Agricultural census data and land use modelling. *Comp Environ Urban Syst* 30(6):799–814. doi:10.1016/j.compenvurbysys.2005.06.003
- Achten WMJ, Vandenbempt P, Almeida J, Mathijs E, Muys B (2010) Life cycle assessment of a palm oil system with simultaneous production of biodiesel and cooking oil in cameroon. *Environ Sci Technol* 44(12):4809–4815. doi:10.1021/es100067p
- Adjei-Nsiah S, Sakyi-Dawson O, Kuyper TW (2012) Exploring opportunities for enhancing innovation in agriculture: the case of oil palm production in Ghana. *J Agric Sci* 4(10):212–223
- Agyei-Dwarko D, G Okyere-Boateng (2010) Selection of New Standard Crosses for the Oil Palm (*Elaeis Guineensis* J.) Third Cycle of Selection. *J Ghana Sci Assoc* 12(1)
- Arrieta FRP, Teixeira FN, Yáñez E, Lora E, Castillo E (2007) Cogeneration potential in the Columbian palm oil industry: Three case studies. *Biomass Bioenergy* 31(7):503–511
- Banse M, van Meijl H, Tabeau A, Woltjer G, Hellmann F, Verburg PH (2011) Impact of EU biofuel policies on world agricultural production and land use. *Biomass Bioenergy* 35(6):2385–2390
- Benoist A, Dron D, Zoughaib A (2012) Origins of the debate on the life-cycle greenhouse gas emissions and energy consumption of first-generation biofuels – A sensitivity analysis approach. *Biomass Bioenergy* 40:133–142. doi:10.1016/j.biombioe.2012.02.011
- Brandão M, Milà i Canals L, Clift R (2011) Soil organic carbon changes in the cultivation of energy crops: Implications for GHG balances and soil quality for use in LCA. *Biomass Bioenergy* 35(6):2323–2336. doi:10.1016/j.biombioe.2009.10.019
- Bringezu S (2009) Assessing Biofuels. ISBN: 978-92-807-3052-4
- Bringezu S, O'Brien M, Schütz H (2012) Beyond biofuels: Assessing global land use for domestic consumption of biomass: A conceptual and empirical contribution to sustainable management of global resources. *Land Use Policy* 29(1):224–232. doi:10.1016/j.landusepol.2011.06.010
- Buratti C, Fantozzi F (2010) Life cycle assessment of biomass production: Development of a methodology to improve the environmental indicators and testing with fiber sorghum energy crop. *Biomass Bioenergy* 34(10):1513–1522
- Carter C, Finley W, Fry J, Jackson D, Willis L (2007) Palm oil markets and future supply. *Eur J Lipid Sci Technol* 109(4):307–314
- Chavalparit O (2003) Industrial ecosystems in the crude palm oil industry in Thailand. In: Inrefagits Working Conference, p 1046
- Chavalparit O, Rulkens WH, Mol APJ, Khaothair S (2006) Options for environmental sustainability of the crude palm Oil industry in thailand through enhancement of industrial ecosystems. *Environ Dev Sustain* 8(2):271–287
- Chen SS (2008) The LCA approach to illustrate palm Oil's sustainability advantage. In: International Palm Oil Sustainability Conference, Sabah
- Choo Y, Muhamad H, Hashim Z, Subramaniam V, Puah C, Tan Y (2011) Determination of GHG contributions by subsystems in the oil palm supply chain using the LCA approach. *Int J Life Cycle Assess* 16(7):669–681. doi:10.1007/s11367-011-0303-9
- Cocklin CR (1989) Methodological problems in evaluating sustainability. *Environ Conserv* 16(4):343–351. doi:10.1017/S0376892900009772
- Corley RH, Tinker PB (2003) The palm oil, 4th edn. Blackwell, Oxford
- Corley RH, Gray BS, Ng SK (1971) Productivity of the oil palm (*Elaeis guineensis* Jacq.). *Expl Agric* 7:129–136
- de Vries SC, van de Ven GWJ, van Ittersum MK, Giller KE (2010) Resource use efficiency and environmental performance of nine major biofuel crops, processed by first-generation conversion techniques. *Biomass Bioenergy* 34(5):588–601. doi:10.1016/j.biombioe.2010.01.001
- Di Lucia L, Ahlgren S, Ericsson K (2012) The dilemma of indirect land-use changes in EU biofuel policy – An empirical study of policy-

- making in the context of scientific uncertainty. *Environ Sci Policy* 16:9–19. doi:[10.1016/j.envsci.2011.11.004](https://doi.org/10.1016/j.envsci.2011.11.004)
- Dumelin E, Rao V, Smith BG, Corley RH (2002) Sustainable Palm oil agriculture - The Unilever initiative. *International Palm Oil Conference, Nusa Dua*, pp 226–237
- EC (2003) Directive 2003/30/EC of the European parliament and of the council of 8 May 2003 on the promotion of the use of biofuels or other renewable fuels for transport
- EC (2012) Proposal for a Directive of the European parliament and of the council amending Directive 98/70/EC relating to the quality of petrol and diesel fuels and amending Directive 2009/28/EC on the promotion of the use of energy from renewable sources
- Edward C, Leonard EGP, Cahn A (1999) Proceedings of the world conference on palm and coconut oils for the 21st century. The American Oil Chemists Society, Denpasar
- Edwards R (2007) Well-to-Wheels analysis of future automotive fuels and powertrains on the European context. EU JRC
- EU (2009) Directive 2009/28/EC of the European parliament and of the council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC.
- Flesch TK, Desjardins RL, Worth D (2011) Fugitive methane emissions from an agricultural biodigester. *Biomass Bioenergy* 35(9):3927–3935. doi:[10.1016/j.biombioe.2011.06.009](https://doi.org/10.1016/j.biombioe.2011.06.009)
- FNR (2009) Biogas-Messprogramm II
- Gawel E, Ludwig G (2011) The iLUC dilemma: How to deal with indirect land use changes when governing energy crops? *Land Use Policy* 28(4):846–856. doi:[10.1016/j.landusepol.2011.03.003](https://doi.org/10.1016/j.landusepol.2011.03.003)
- Goh KJ (2005) Fertilizer recommendation system for oil palm: estimating the fertilizer rates. In: Chew PS, Tan YP (eds) MOSTA Best Practice Workshops - Agronomy and Crop Management, Malaysian Oil Scientists and Technologists Association, pp 253–268
- Hedal Kløverpris J, Baltzer K, Nielsen P (2010) Life cycle inventory modelling of land use induced by crop consumption. *Int J Life Cycle Assess* 15(1):90–103. doi:[10.1007/s11367-009-0132-2](https://doi.org/10.1007/s11367-009-0132-2)
- Henson IE (1999) Comparative ecophysiology of oil palm and tropical rain forest In: Oil palm and the environment. Malaysian Oil Palm Growers' Council, Kuala Lumpur
- Henson IR, Ruiz R, Romero HM (2011) The growth of the oil palm industry in Columbia. *J Palm Oil Res* 23:1121–1128
- Idris MSH (2003) Fattening of beef cattle with oil palm by-products – Oil palm frond based diets. In: Forages and feed resources in commercial livestock production systems. 8th meeting of the regional working group on grazing and feed resources for Southeast Asia, Kuala Lumpur, pp 71–75
- IPCC (2006a) IPCC Guidelines for National Greenhouse Gas Inventories (Agriculture)
- IPCC (2006b) Waste (Vol.5, Chapter 4). Available at: <http://www.ipccnggip.iges.or.jp/public/>
- Jungbluth N, Chudacoff M, Dauriat A, Dinkel F, Doka G, Emmenegger F, Gnansounou E, Kljun N, Schleiss K, Spielmann M, Stettler C, Sutter J (2007) Life cycle inventories of bioenergy. vol ecoinvent report No. 17. Swiss Centre for Life Cycle Inventories, Dübendorf
- Kaewmai R, H-Kittikun A, Musikavong C (2012) Greenhouse gas emissions of palm oil mills in Thailand. *Int J Greenh Gas Control* 11: 141–151. doi:[10.1016/j.jggc.2012.08.006](https://doi.org/10.1016/j.jggc.2012.08.006)
- Kaewmai R, H-Kittikun A, Suksaroj C, Musikavong C (2013) Alternative Technologies for the Reduction of Greenhouse Gas Emissions from Palm Oil Mills in Thailand. *Environ Sci Technol*. doi:[10.1021/es4020585](https://doi.org/10.1021/es4020585)
- Kamahara H, Hasanudin U, Widiyanto A, Tachibana R, Atsuta Y, Goto N, Daimon H, Fujie K (2010) Improvement potential for net energy balance of biodiesel derived from palm oil: A case study from Indonesian practice. *Biomass and Bioenergy*. doi:[10.1016/j.biombioe.2010.07.014](https://doi.org/10.1016/j.biombioe.2010.07.014)
- Khalid H, Zin ZZ, Anderson JM (2000) Decomposition processes and nutrient release patterns of oil palm residues. *J Oil Palm Res* 12(1): 46–63
- Kim S, Dale BE (2011) Indirect land use change for biofuels: testing predictions and improving analytical methodologies. *Biomass Bioenergy* 35(7):3235–3240. doi:[10.1016/j.biombioe.2011.04.039](https://doi.org/10.1016/j.biombioe.2011.04.039)
- Kittikun HP, Prasertsan P, Srisuwan G, Krause A (2000) Environmental management for palm oil mill. In: Internet Conference on Material Flow Analysis of Integrated Bio-System
- Lam MK, Lee KT, Mohamed AR (2009) Life cycle assessment for the production of biodiesel: a case study in Malaysia for palm oil versus jatropha oil. *Biofuels Bioprod Bioref* 3(6):601–612. doi:[10.1002/bbb.182](https://doi.org/10.1002/bbb.182)
- Levasseur A, Lesage P, Margni M, Samson R (2012) Biogenic carbon and temporary storage addressed with dynamic life cycle assessment. *J Ind Ecol*. doi:[10.1111/j.1530-9290.2012.00503.x](https://doi.org/10.1111/j.1530-9290.2012.00503.x)
- Malins C (2012) Comments of the ICCT on EPA palm oil pathway NODA. International Council on Clean Transportation, Washington San Francisco
- Manik Y, Halog A (2013) A meta-analytic review of life cycle assessment and flow analyses studies of palm oil biodiesel. *Integr Environ Assess Manag* 9(1):134–141. doi:[10.1002/ieam.1362](https://doi.org/10.1002/ieam.1362)
- Melling L, Hatano R, Goh KJ (2005) Global warming potential from soils in tropical peatland of Sarawak, Malaysia. *Phyton-Annales Rei Botanicae* 45(4):275–284
- Melling L, Hatano R, Goh KJ, Inioe T (2006) Greenhouse gas fluxes from three ecosystems in tropical peatland of Sarawak, Malaysia. Paper presented at the 18th World Congress of Soil Science, Philadelphia
- Melling L, Goh KJ, Bouvais C, Hatano R (2010) Carbon flow and budget in a young mature oil palm agroecosystem on deep tropical peat. <http://www.geog.le.ac.uk/carbopeat/media/pdf/yogyapapers/p43.pdf>.
- Müller-Wenk R, Brandão M (2010) Climatic impact of land use in LCA—carbon transfers between vegetation/soil and air. *Int J Life Cycle Assess* 15(2):172–182. doi:[10.1007/s11367-009-0144-y](https://doi.org/10.1007/s11367-009-0144-y)
- Ng SK, Thamboo S (1967) Nutrient content of oil palms in Malaya. *Malays Agric J* 46:3–45
- Ng S, Thamboo S, De Souza P (1968) Nutrient content of oil palms in Malaya II. Nutrient in vegetative tissues. *Malays Agric J* 46:332–391
- O'Hare M, Delucchi M, Edwards R, Fritsche U, Gibbs H, Hertel T, Hill J, Kammen D, Laborde D, Marelli L, Mulligan D, Plevin R, Tyner W (2011) Comment on “Indirect land use change for biofuels: testing predictions and improving analytical methodologies” by Kim and Dale: statistical reliability and the definition of the indirect land use change (iLUC) issue. *Biomass Bioenergy* 35(10):4485–4487. doi:[10.1016/j.biombioe.2011.08.004](https://doi.org/10.1016/j.biombioe.2011.08.004)
- Papong S, Chom-In T, Noksa-nga S, Malakul P (2010) Life cycle energy efficiency and potentials of biodiesel production from palm oil in Thailand. *Energy Policy* 38(1):226–233
- Pleanjai S, Gheewala SH (2009) Full chain energy analysis of biodiesel production from palm oil in Thailand. *Appl Energy* 86(Supplement 1):S209–S214
- Pleanjai S, Gheewala S, Garivait S (2004) Environmental evaluation of biodiesel production from palm oil in a life cycle perspective. The Joint International Conference on “Sustainable Energy and Environment (SEE)”, Hua Tin, pp 604–608
- Poh PE, Chong MF (2009) Development of anaerobic digestion methods for palm oil mill effluent (POME) treatment. *Bioresour Technol* 100(1):1–9. doi:[10.1016/j.biortech.2008.06.022](https://doi.org/10.1016/j.biortech.2008.06.022)
- Rafflegau S, Michel-Dounias I, Tailliez B, Ndigu B, Papy F (2010) Unexpected N and K nutrition diagnosis in oil palm smallholdings using references of high-yielding industrial plantations. *Agron Sustain Dev* 30(4):777–787. doi:[10.1051/agro/2010019](https://doi.org/10.1051/agro/2010019)

- Rettenmaier N, Reinhardt G, Muench J, Gaertner S (2007) Datenprojekt “Nachwachsende Rohstoffe”. IFEU, Heidelberg-Karlsruhe
- Saikku L, Soimakallio S, Pingoud K (2012) Attributing land-use change carbon emissions to exported biomass. *Environ Impact Assess Rev* 37:47–54. doi:[10.1016/j.eiar.2012.03.006](https://doi.org/10.1016/j.eiar.2012.03.006)
- Schmidt JH (2004) The importance of system boundaries for LCA on large material flows of vegetable oils. Fourth World SETAC Congress, Portland
- Secchi S, Kurkalova L, Gassman PW, Hart C (2011) Land use change in a biofuels hotspot: the case of Iowa, USA. *Biomass Bioenergy* 35(6): 2391–2400
- Siriwardhana M, Opathella GKC, Jha MK (2009) Bio-diesel: Initiatives, potential and prospects in Thailand: A review. *Energy Policy* 37(2): 554–559
- Stichnothe H, Schuchardt F (2010) Comparison of different treatment options for palm oil production waste on a life cycle basis. *Int J Life Cycle Assess* 15(9):907–915. doi:[10.1007/s11367-010-0223-0](https://doi.org/10.1007/s11367-010-0223-0)
- Stichnothe H, Schuchardt F (2011) Life cycle assessment of two palm oil production systems. *Biomass Bioenergy* 35(9):3976–3984. doi:[10.1016/j.biombioe.2011.06.001](https://doi.org/10.1016/j.biombioe.2011.06.001)
- Subramaniam V, Ngan MA, May CY, Sulaiman NMN (2008) Environmental performance of the milling process of Malaysian palm Oil using the life cycle assessment approach. *Am J Environ Sci* 208(4):310–315
- Sulaiman F, Abdullah N, Gerhauser H, Shariff A (2011) An outlook of Malaysian energy, oil palm industry and its utilization of wastes as useful resources. *Biomass Bioenergy* 35(9):3775–3786. doi:[10.1016/j.biombioe.2011.06.018](https://doi.org/10.1016/j.biombioe.2011.06.018)
- Tarmizi AM, Mohd Tayeb D (2006) Nutrient demands of Tenera oil palm planted on islands of Malaysia. *J Oil Palm Res* 18(June):204–209
- Tarmizi AM, Haron K, Omar W (2006) Environmental aspects of agro-nomic practices of oil palm plantation. International Oil Palm Conference, Nusa Dua, pp 60–77
- Thamsiriroj T, Murphy JD (2009) Is it better to import palm oil from Thailand to produce biodiesel in Ireland than to produce biodiesel from indigenous Irish rape seed? *Appl Energy* 86(5):595–604
- Thamsiriroj T, Murphy JD (2010a) Can rape seed biodiesel meet the European union sustainability criteria for biofuels? *Energy Fuel* 24(3):1720–1730. doi:[10.1021/ef901432g](https://doi.org/10.1021/ef901432g)
- Thamsiriroj T, Murphy JD (2010b) How much of the target for biofuels can be met by biodiesel generated from residues in Ireland? *Fuel* 89(11):3579–3589
- UNFCCC (2010) Indicative simplified baseline and monitoring methodologies for selected small-scale CDM project activity categories
- Wahid MB, Abdullah SNA, Henson IE (2005) Oil palm - Achievements and potential. *Plant Prod Sci* 8(3):288–297
- Wan Zahari M, Sato J, Furuichi S, Azizan AR, Yunus M (2003) Commercial processing of oil palm fronds feed in Malaysia. In: Forages and feed resources in commercial livestock production systems. 8th meeting of the regional working group on grazing and feed resources for Southeast Asia, Kuala Lumpur, Malaysia. pp 59–65
- Wicke B, Dornburg V, Faaij A, Junginger M (2007) A greenhouse gas balance of electricity production from co-firing palm oil products from Malaysia. vol Final Report. University Utrecht, Copernicus Institute, Department of Science, Technology and Society
- Wicke B, Dornburg V, Junginger M, Faaij A (2008) Different palm oil production systems for energy purposes and their greenhouse gas implications. *Biomass Bioenergy* 32(12):1322–1337
- Wulfert K, Darnoko D, Tobing PL, Yulisari R, Guritno P (2002) Treatment of POME in anaerobic fixed bed digesters. In: International Oil Palm Conference IOPC, pp 265–275
- Yee KF, Tan KT, Abdullah AZ, Lee KT (2009) Life cycle assessment of palm biodiesel: Revealing facts and benefits for sustainability. *Appl Energy* 86:S189–S196
- Yoshizaki T, Shirai Y, Hassan MA, Baharuddin AS, Raja Abdullah NM, Sulaiman A, Busu Z (2013) Improved economic viability of integrated biogas energy and compost production for sustainable palm oil mill management. *J Clean Prod* 44:1–7. doi:[10.1016/j.jclepro.2012.12.007](https://doi.org/10.1016/j.jclepro.2012.12.007)